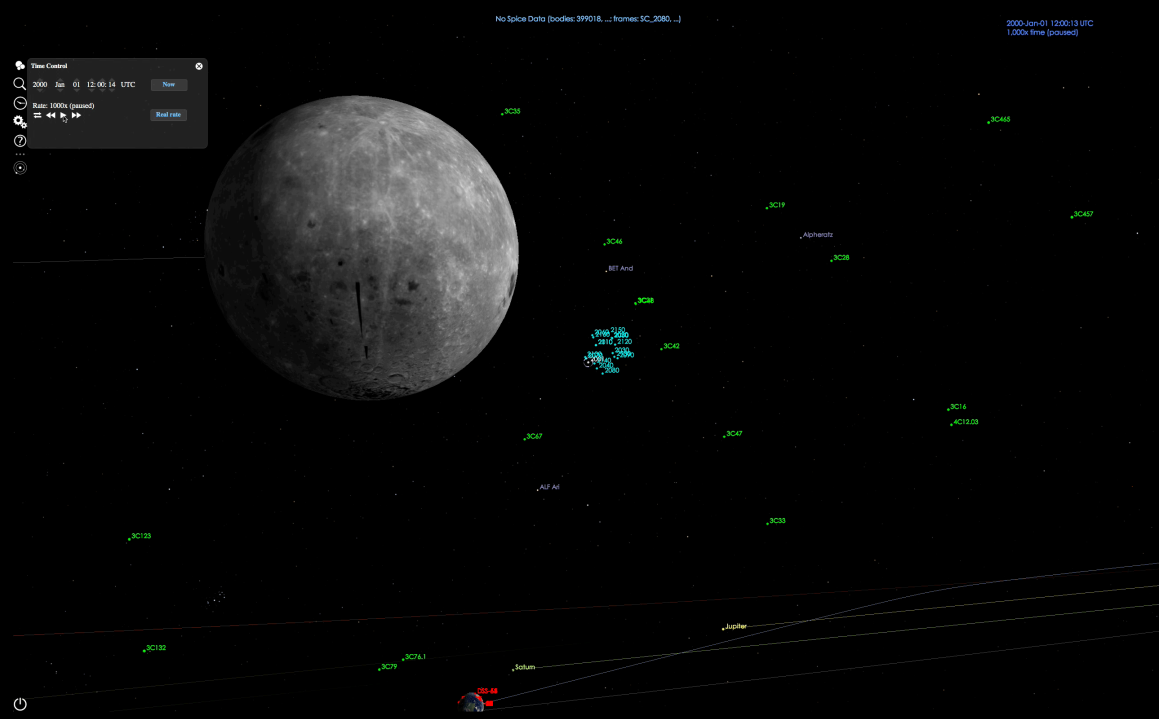
Preliminary Results of Heuristic Guided Orbit Selection for a Low Frequency Radio Interferometric Spacecraft Constellation

Andrew Branch, Steve Schaffer, Steve Chien,
Sonia Hernandez

Jet Propulsion Laboratory, California Institute of Technology

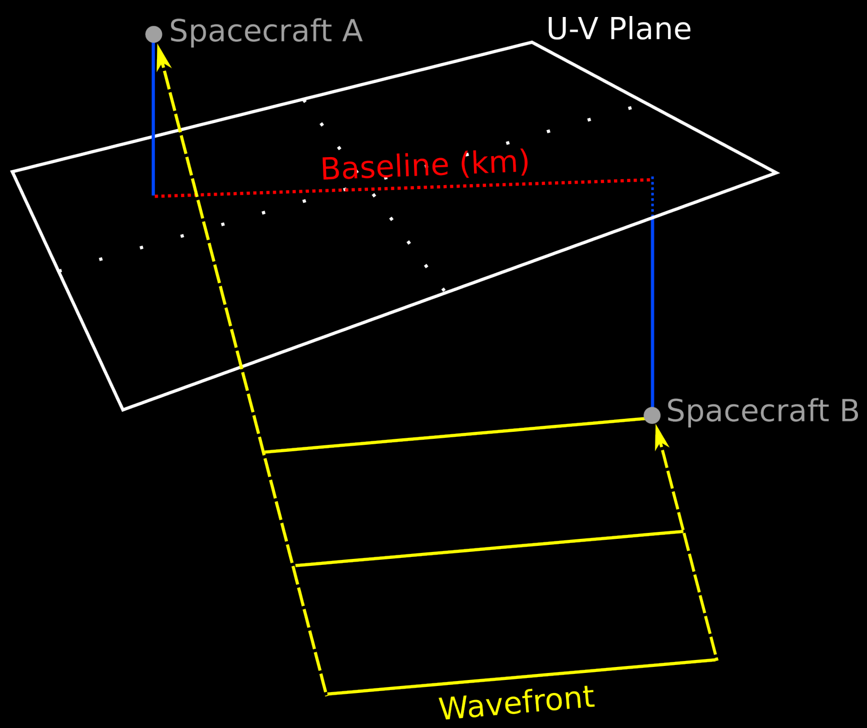
Radio-Interferometry Mission Concept

- Space based radio-frequency interferometry array
- 2-128 radio telescope spacecraft in lunar orbit
- Single mothership to relay data to Earth
- Targets are approximately uniformly distributed extra-galactic sources



Radio-Frequency Interferometry

- Combine signals from multiple antenna to synthesis a larger antenna
- Varying antenna baselines and orientations provides more information
  - Terrestrial arrays use Earth's rotation to achieve different baselines
  - Constellation would use orbital motion to achieve different baselines



Problem

Single Craft Orbit Definition

$$o(t) \rightarrow \langle a_r, i_r, \Omega_r, \nu_r \rangle$$

Candidate Solution

$$s = \underbrace{\{o_1(t) \ldots o_n(t)\}}_{\text{Subset of all orbits}}$$

Constraints

$$C(s) \rightarrow \{\text{true}, \text{false}\}$$

Weighted Utility Functions

$$E(s) \rightarrow \Re$$

$$w \in \Re$$

Overall Solution Quality

$$Q(s) = \underbrace{\sum_{i=1}^{m} w_i E_i(S)}_{\text{Weighted sum of utility functions}}$$

Final Solutions

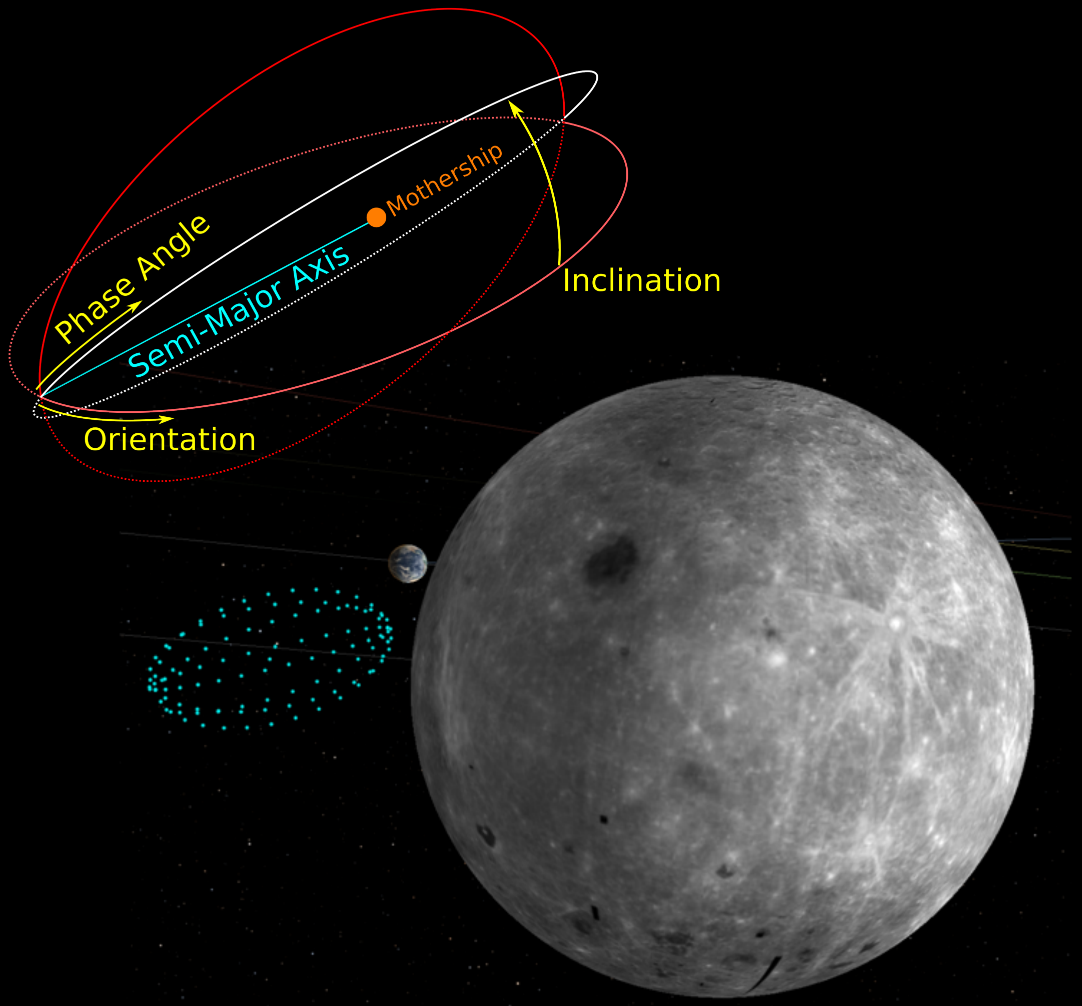
$$S' = \underbrace{\{s \mid C(s) = \text{true}\, \forall C \in \{C_1 \ldots C_n\}\}}_{\text{Set of solutions that obey constraints}}$$

$$S'' = \underbrace{\arg\max_{s \in S'} Q(s)}_{\text{Solution with best quality score}}$$

Constellation Structure

- Elliptical rings defined by semi-major axis, inclination, orientation, and phase angle

- Spacecraft orbits continuously change projected baselines and orientations

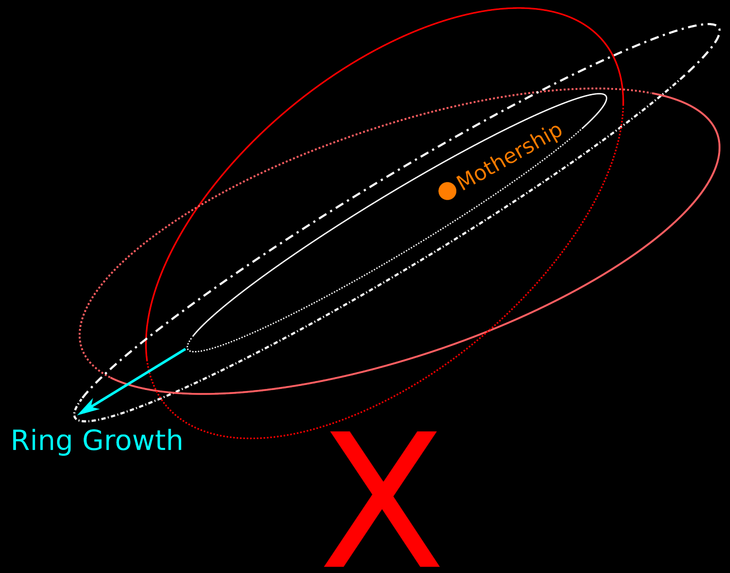


Ring Growth

- Rings can be expanded at cost of Δv
- Rings cannot cross to avoid spacecraft collisions
- Allows for reaching longer baselines

Invalid

Rings cross



Valid

No rings cross

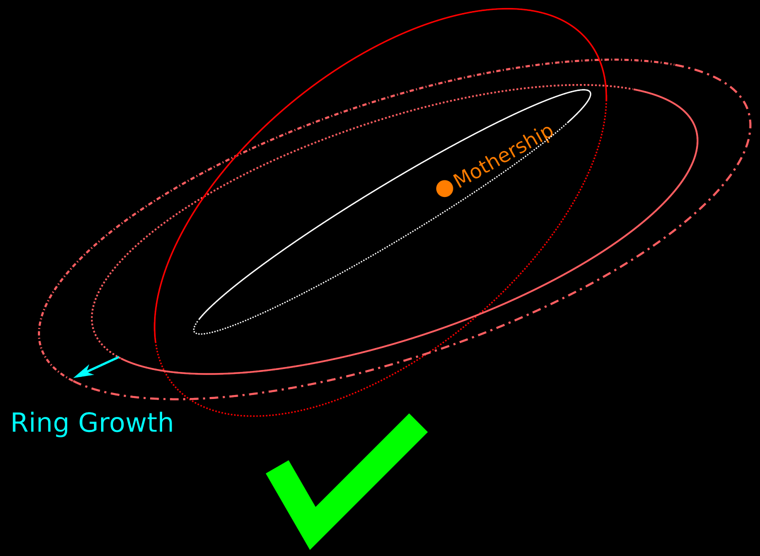
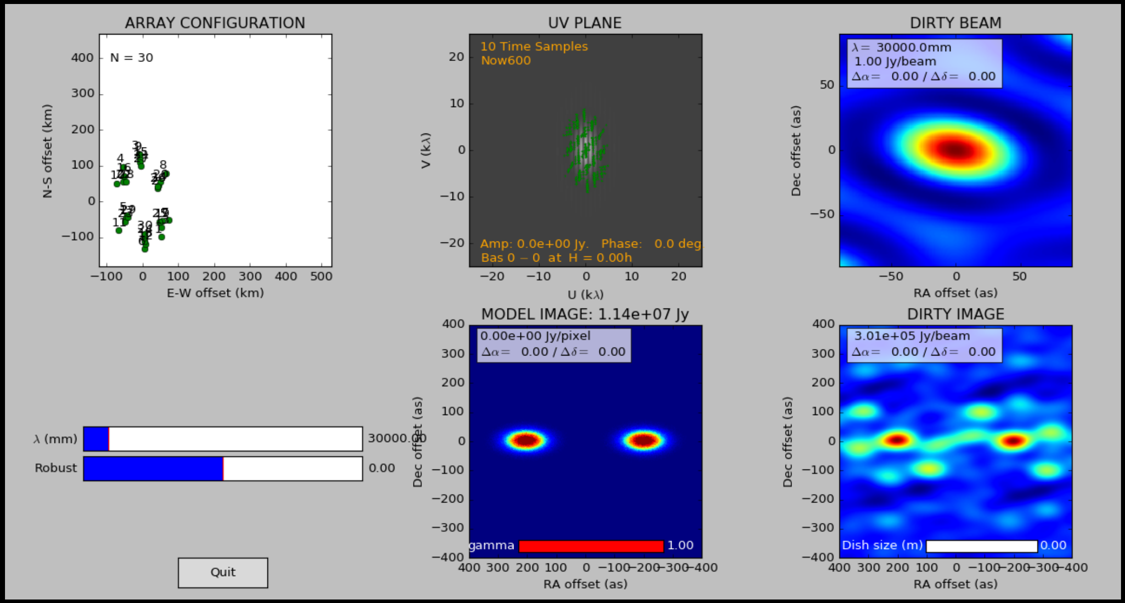


Image Reconstruction Fidelity

- Simulate aperture synthesis with baselines from constellation over 1 orbit
- Compare resulting synthesized image to model image using RMS error
- Computationally intensive, ~4 hours for 1 orbit

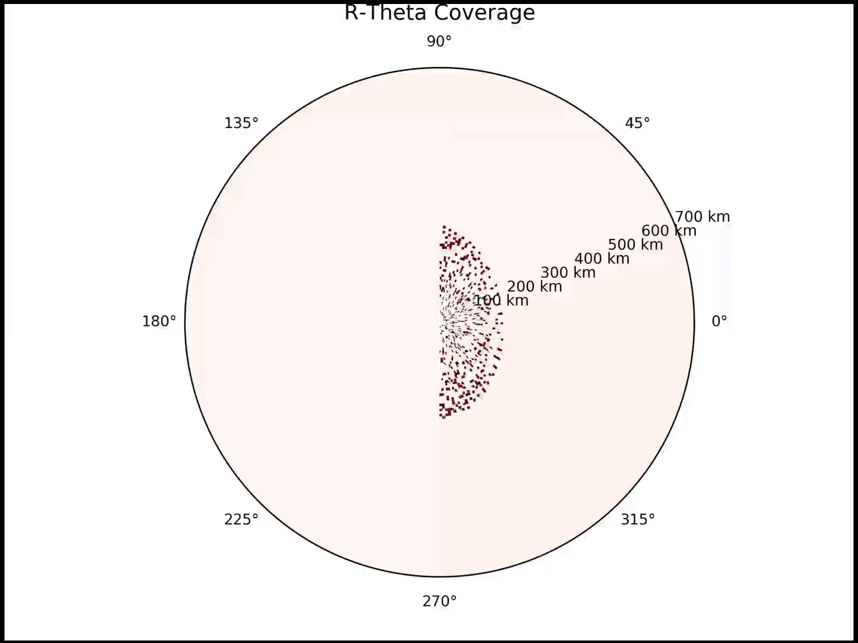


Aperture Synthesis Simulator (APSYNSIM)

Orbit Selection Heuristics

Baseline Coverage Metric

- Metric variables
  - Projected distance between two spacecraft
  - Orientation between two space spacecraft
- Percent coverage of 100 x 100 radial bins
- Spacecraft loss sensitive metric
  - Cubesats have high chance of failure
  - Average coverage over different loss scenarios
- Fast computation times allow use in search, << 1 second for 1 orbit



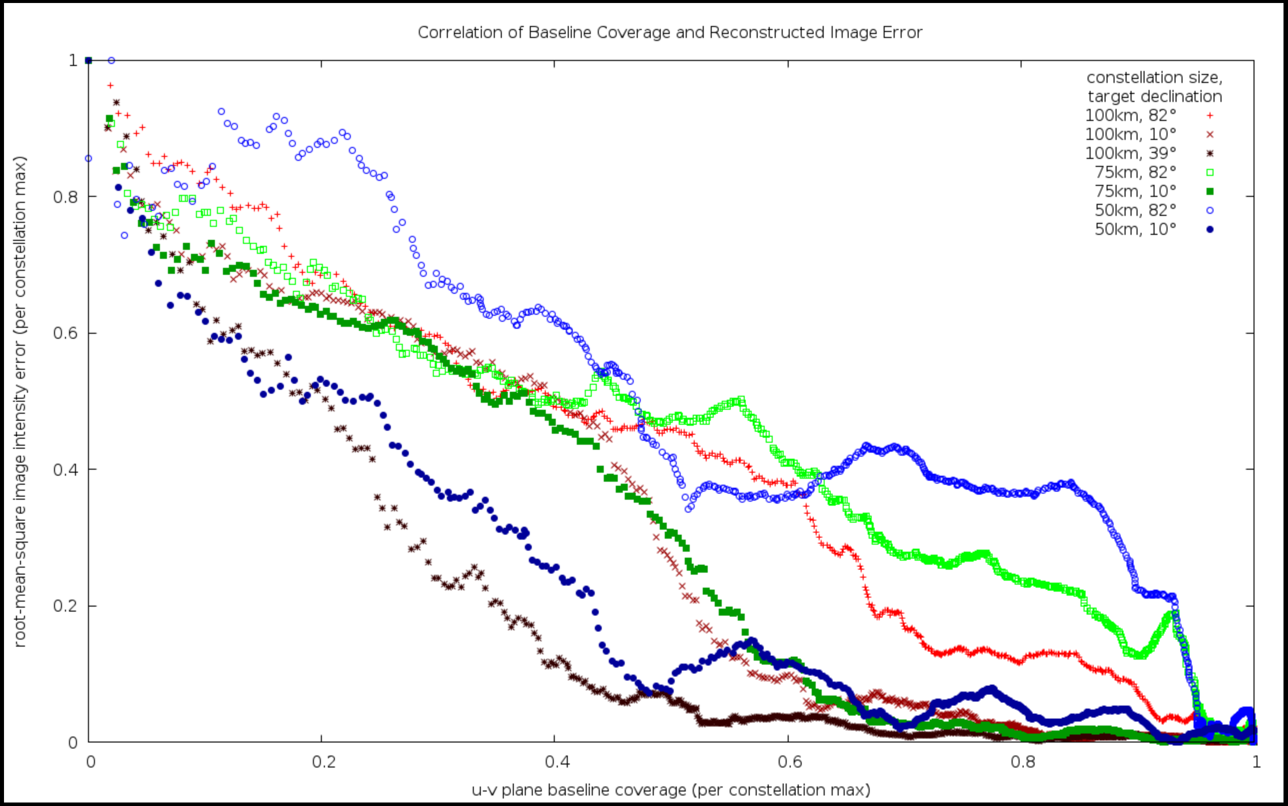
Orbit Selection Heuristics

Heuristic Analysis

Negative correlation between RMS error of reconstructed image and baseline coverage until ~50% coverage

Less correlation after ~50% coverage

Baseline coverage metric is an acceptable proxy for image reconstruction metric

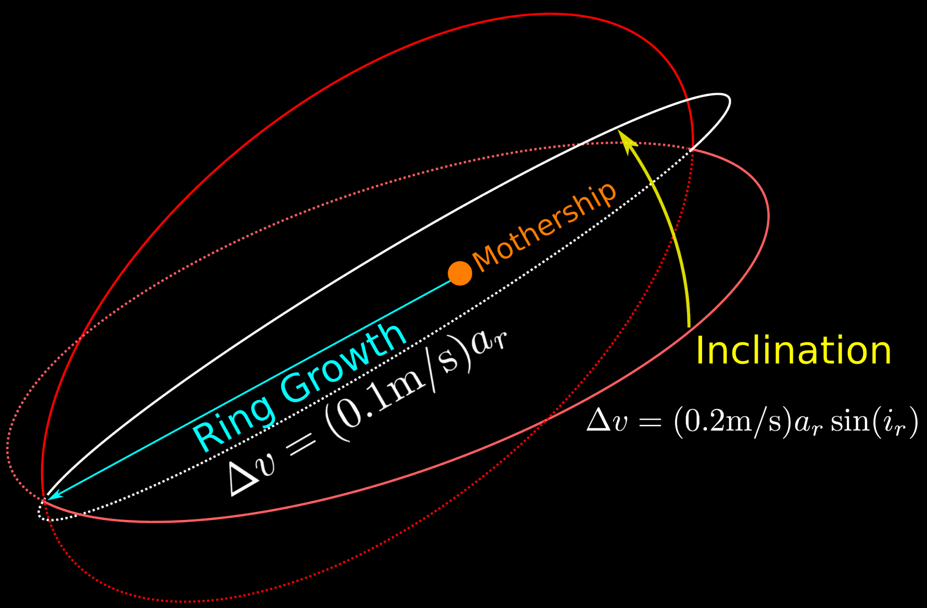


Orbit Selection Heuristics

Fuel Cost Metric

- Two main fuel cost for spacecraft, ring growth and inclination

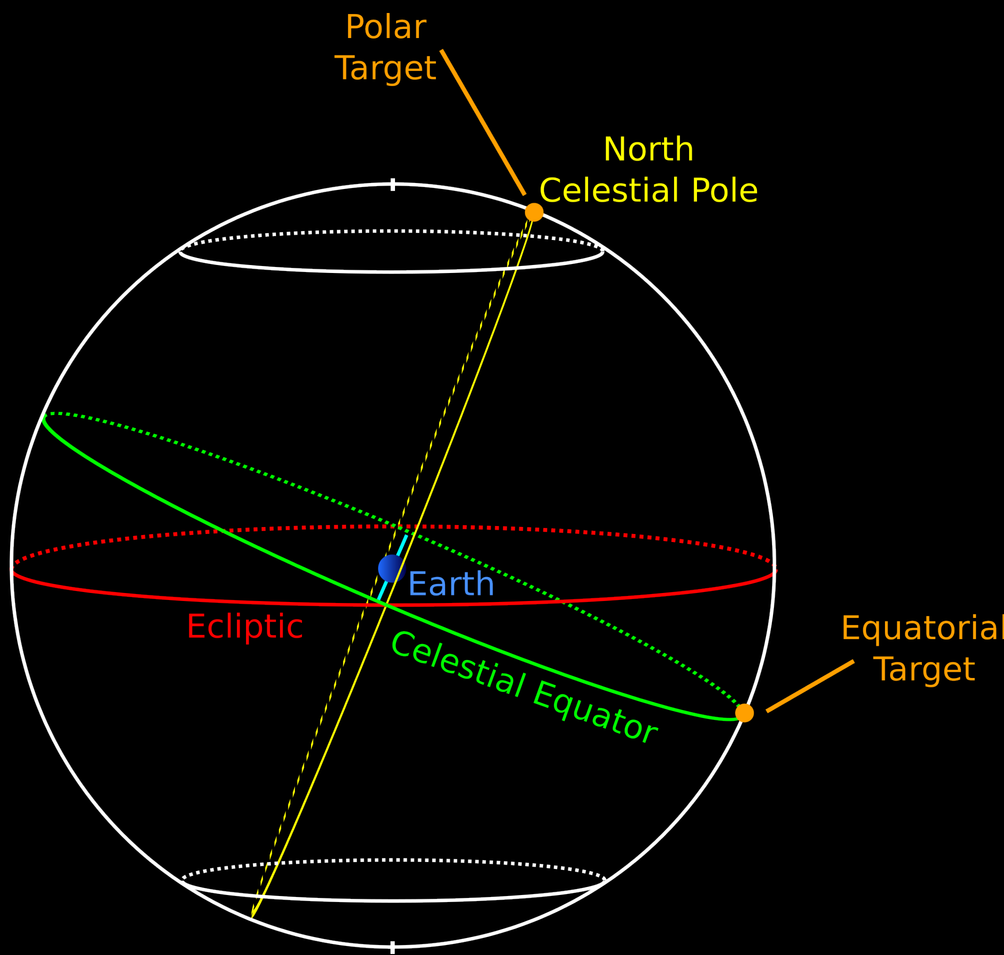
- Fuel Cost Equation
  - a_r - Semi-major axis of ring
  - i_r - Inclination of ring
  - I_{sp} - Specific impulse



$$f(o) \propto I_{sp}^{-1}((0.1\mathrm{m/s})a_r + (0.2\mathrm{m/s})a_r \sin(i_r))$$

Full Sky Survey Targets

Celestial Sphere



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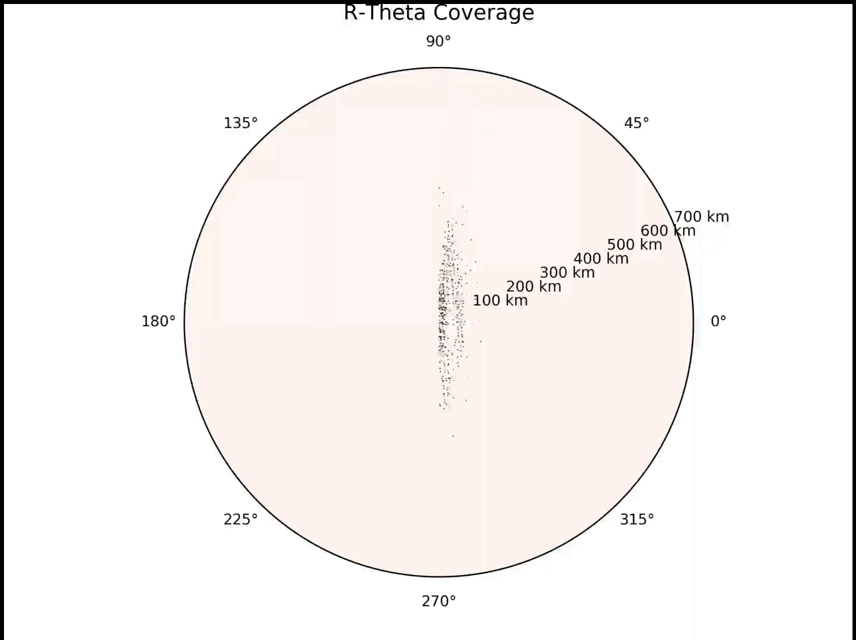
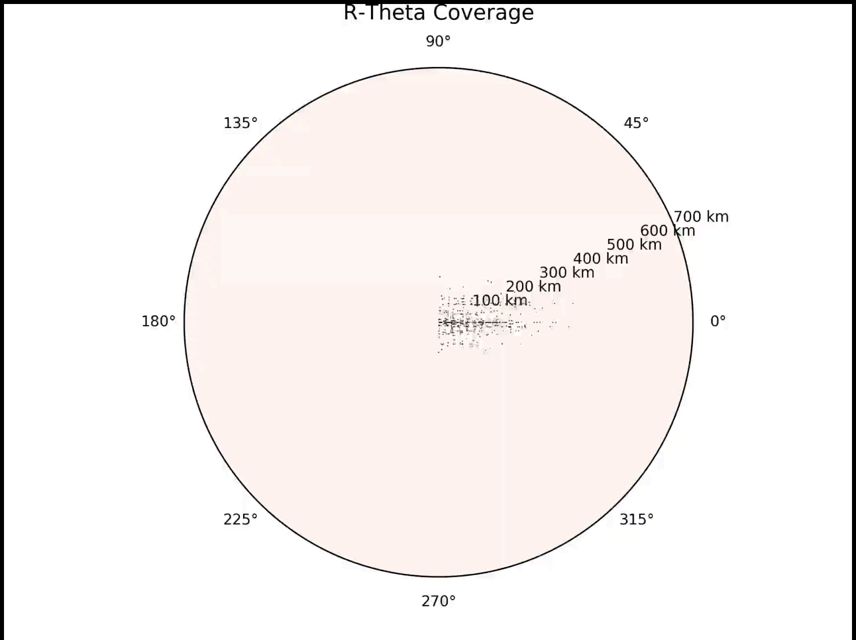
Full Sky Survey

Baseline Coverage Metric

Polar Target

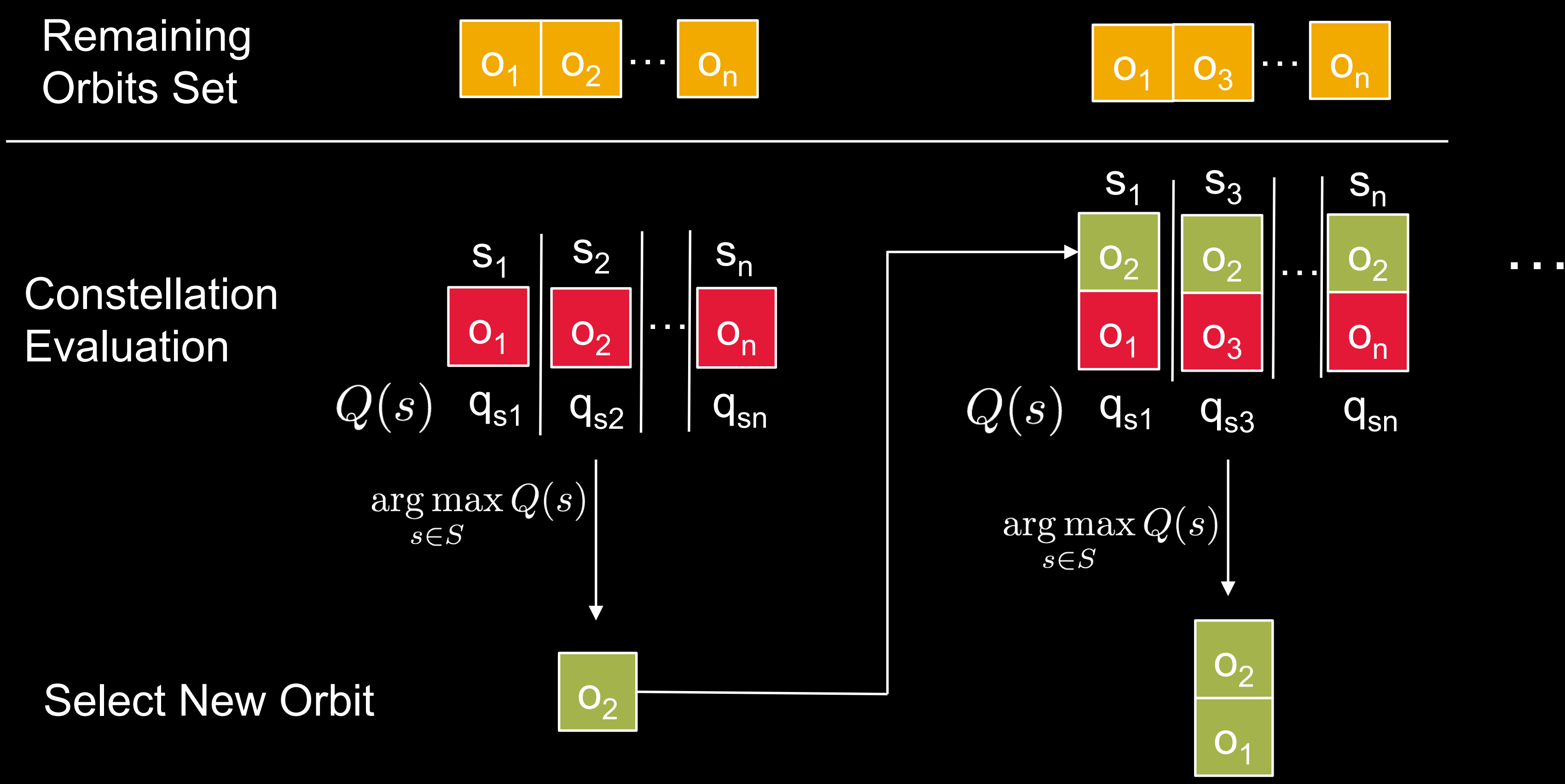


Equatorial Target



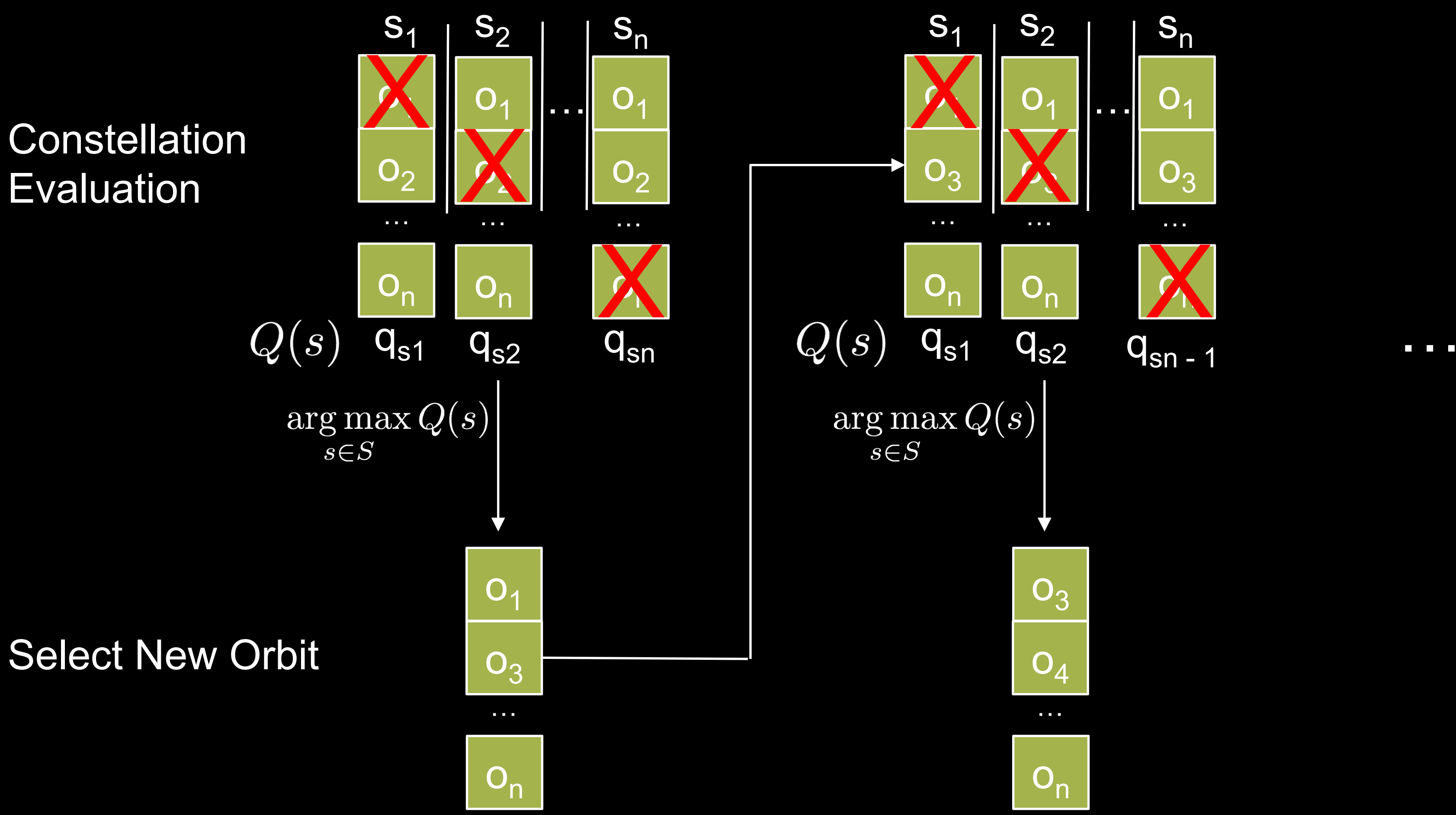
Orbit Selection Algorithm

Forward Greedy Search



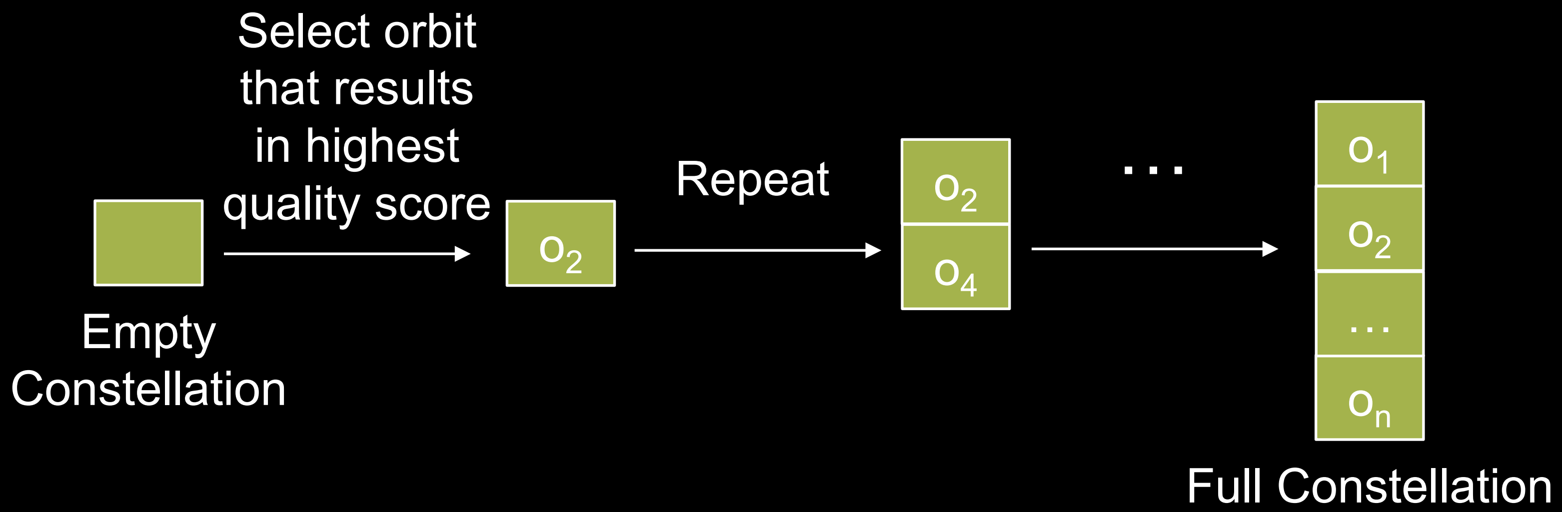
Orbit Selection Algorithm

Reverse Greedy Search



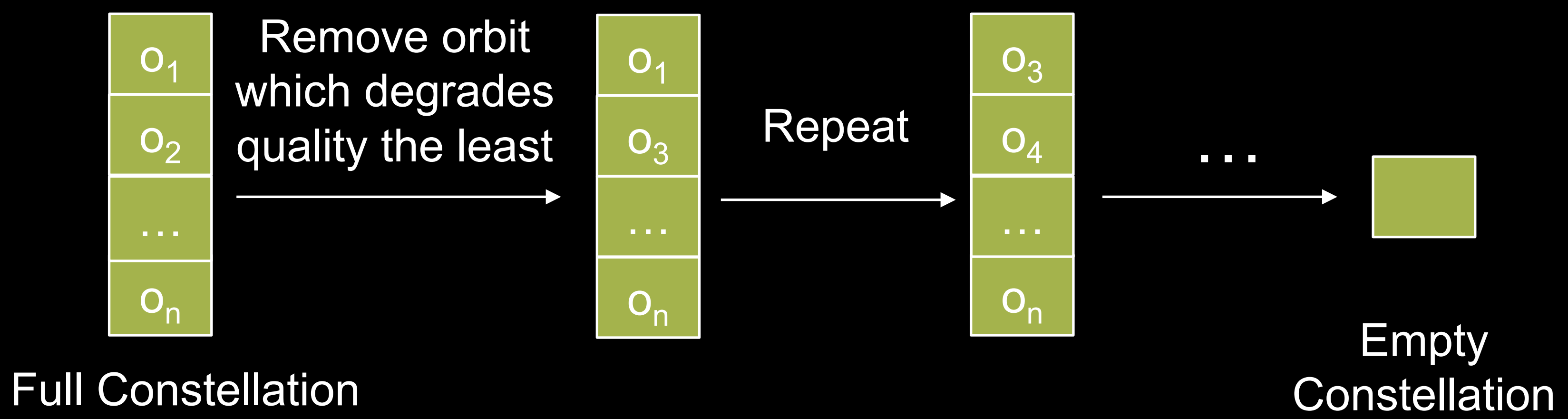
Orbit Selection Algorithm

Forward Greedy Search



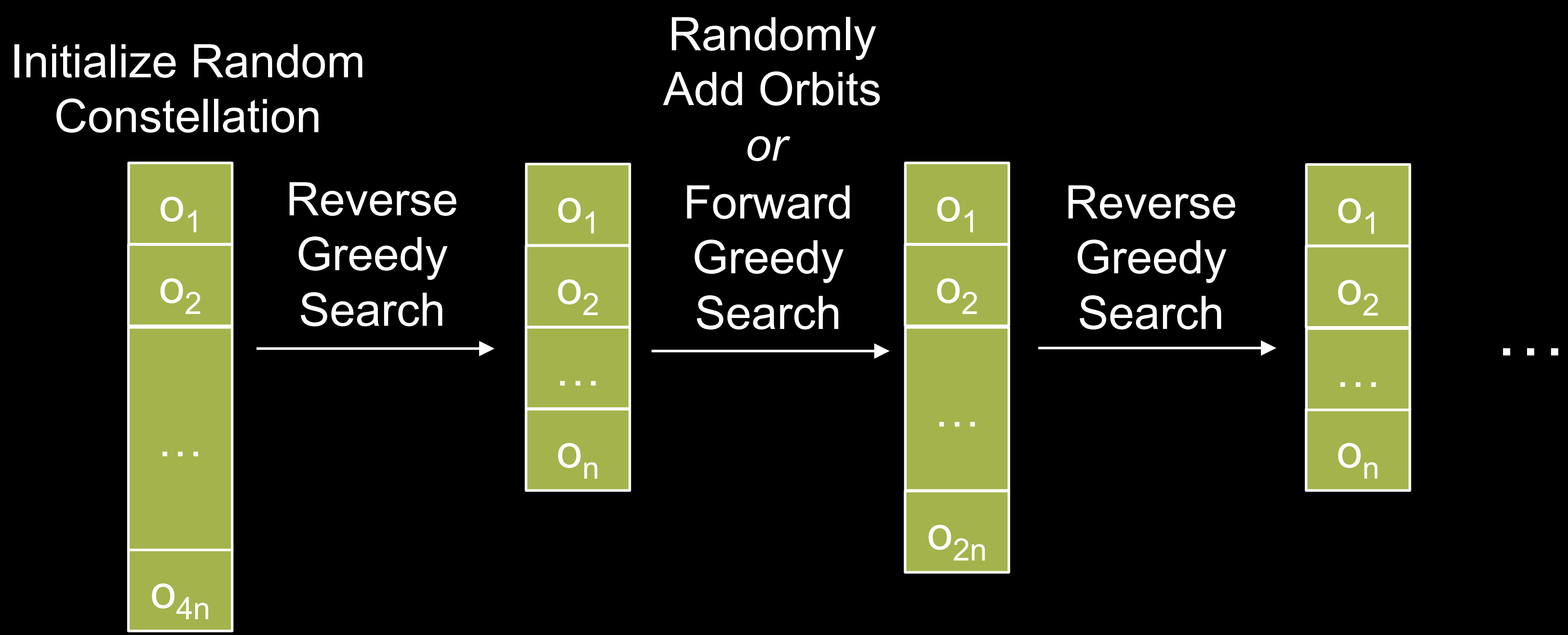
Orbit Selection Algorithm

Reverse Greedy Search



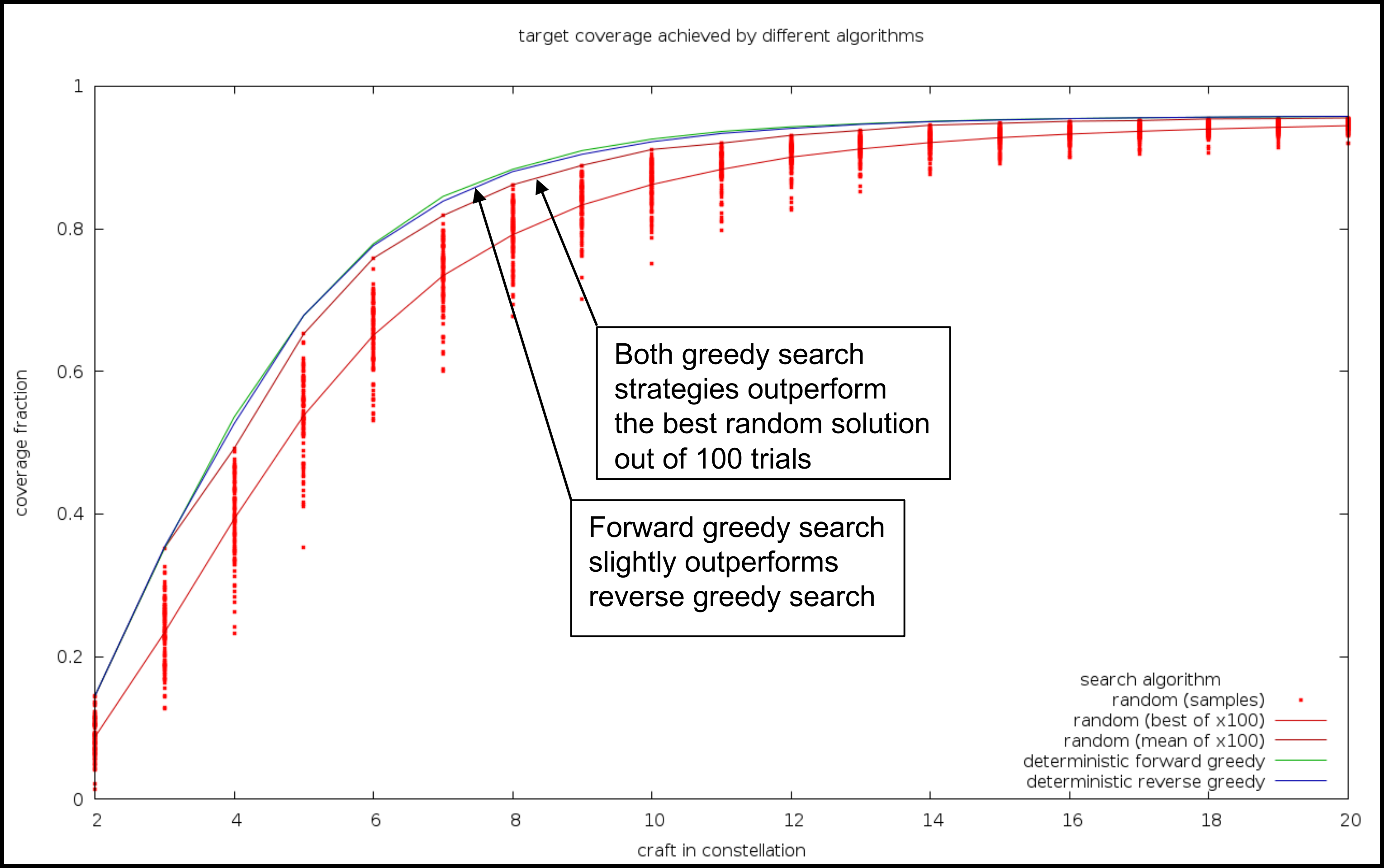
Orbit Selection Algorithm

Bi-Directional Greedy Search



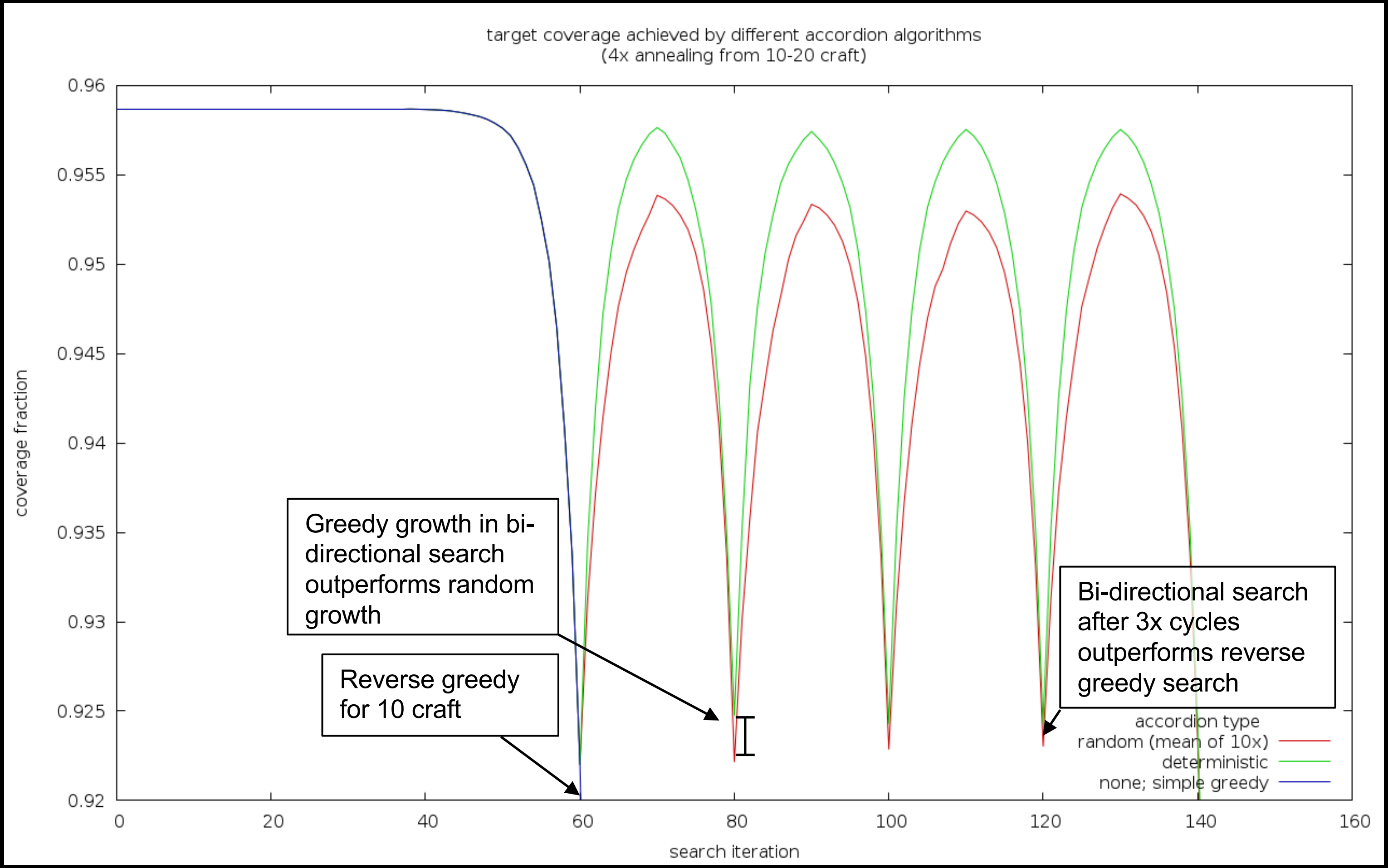
Results

Algorithm Comparison



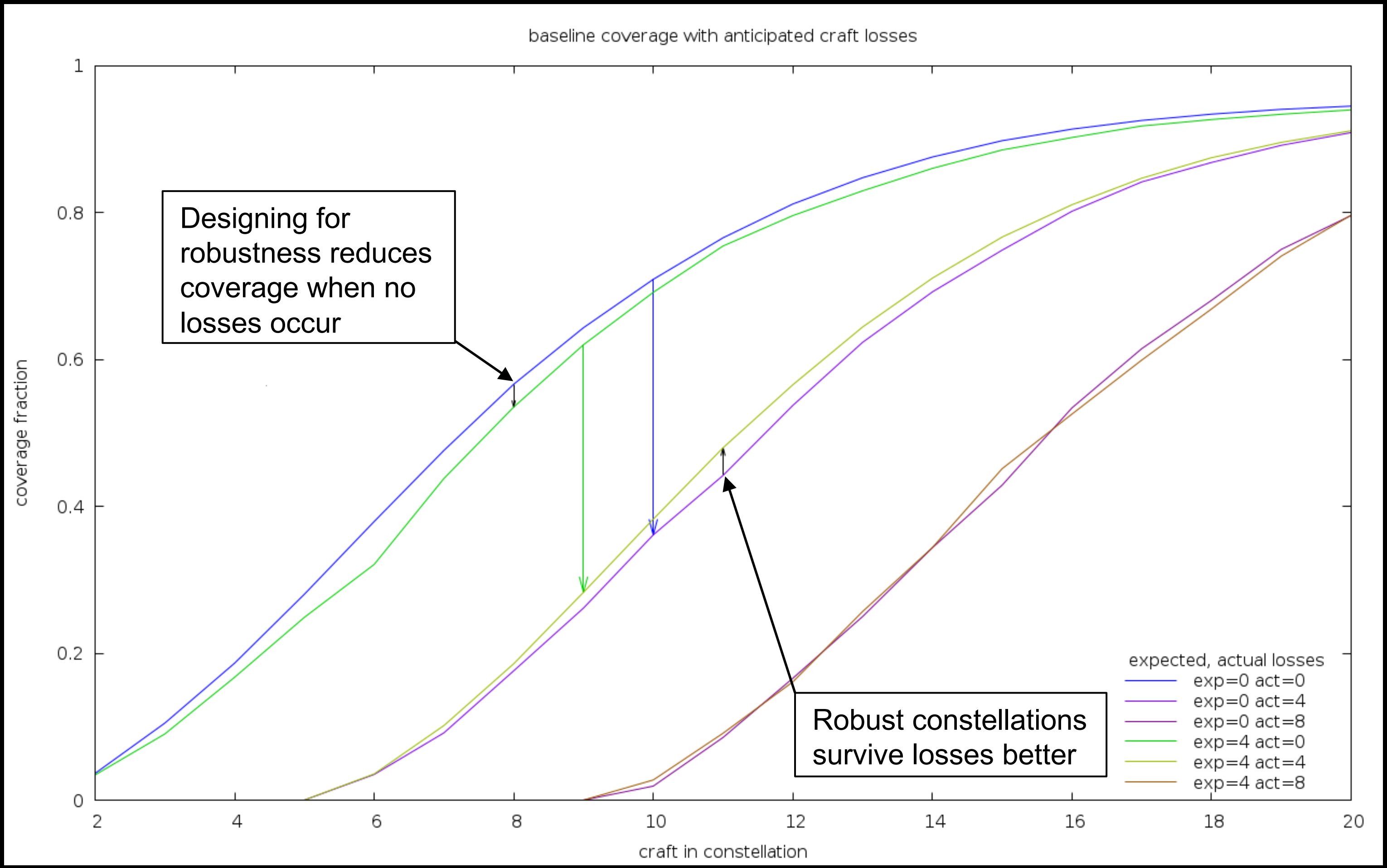
Results

Bi-Directional Algorithm



Results

Loss Sensitive Heuristic



Results

High Inclination Orbits

Equatorial Target

Good Coverage

Polar Target

Good Coverage

Results

Low Inclination Orbits

Equatorial Target

Poor Coverage

Polar Target

Good Coverage

Related Work

Fomalont, E. B. 1973. Earth-rotation aperture synthesis. *IEEE Proceedings* 61:1211–1218. - Using Earth rotation for baseline variety

Hernandez, S.; Garza, D. M.; Broschart, S. B.; Herzig, S. J. I.; and Chien, S. A. 2017. Small satellite constellation to enable a lunar radio interferometer. - Details of orbit generation for our constellation

S. J. I. Herzig and S. Mandutianu and H. Kim and S. Hernandez and T. Imken, IEEE Aerospace Conference 2017. Model-Transformation-Based Computational Design Synthesis for Mission Architecture Optimization. - Multi-spacecraft mission design using a space-based radio interferometry array as a case study

Related Work

Hirosawa, H.; Hirabayashi, H.; Kobayashi, H.; Murata, Y.; Kii, T.; Edwards, P.; Natori, M.; Takano, T.; Yamamoto, Z.- I.; Hashimoto, T.; et al. 1998. Space VLBI satellite HALCA and its engineering accomplishments. In *Proceedings 49th International Astronautical Congress*. - Single satellite extending the earth-based VLBI

Rajan, R. T.; Boonstra, A.-J.; Bentum, M.; Klein-Wolt, M.; Belien, F.; Arts, M.; Saks, N.; and van der Veen, A.-J. 2016. Space-based aperture array for ultra-long wavelength radio astronomy. *Experimental Astronomy* 41(1-2):271–306. - White paper for a space-based low frequency radio interferometer mission

Future Work

- Develop efficiently computed heuristic more related to image reconstruction fidelity
- Extend greedy algorithms to examine multiple joint solution modifications each iterations
- More accurate modelling of orbits
  - Occultations by moon, sun, and planets
  - Effects of Earth gravity on constellation
- Further study of loss of spacecraft
  - Model loss as a Poisson process

Conclusion

- We successfully applied heuristic guided optimization in order to select orbits for a constellation of radio interferometric spacecraft.
- This approach confirmed existing intuition as well as provided fresh insight into the problem.
- This approach allows mission designers to focus on higher quality solutions, increasing productivity, reducing cost, and increasing final mission science return.

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